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ORIGIN OF FOLIATION IN THE PRE-CAMBRIAN ROCKS OF NORTHERN NEW YORK[1]

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INTRODUCTION

Data bearing upon the problem of the origin of foliation in the pre-Cambrian rocks of northern New York have been gathered during the last ten years by the writer while he was engaged in the geological surveys of various quadrangles in the Adirondack Mountain region. In the attempt to explain the origin of the foliated structures of the rocks, examples and analogies from other parts of the world will be introduced, and it is hoped that the conclusions reached may have a wider application than to the Adirondack region alone.

This paper is not much concerned with criteria for the determination of original igneous or sedimentary character of the rocks. The conclusions reached are almost wholly based upon observations made upon rocks which have been generally recognized as quite certainly either igneous or sedimentary. Rocks of rather doubtful origin are frequently met in minor quantity, but these may be disregarded in the present discussion.

The strata all belong to the very ancient Grenville series, including various gneisses and schists, together with crystalline limestone and quartzite. The chief criteria for the determination of their sedimentary origin are: distinct banded structures, often showing alternating layers of widely different composition sharply separated from each other; presence of extensive bodies of limestone and quartzite interbedded with the gneisses; dissemination of graphite flakes through many of the rocks; and the very common occurrence of garnet in many of the rocks, and the less common occurrence of sillimanite.

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[1] Published by permission of the Director of the New York State Museum.

The metamorphic rocks of igneous origin, given in regular order of geologic age, comprise the anorthosite series, the syenite-granite series, and the gabbros, all of which show quite varied degrees of metamorphism. All are intrusive rocks and younger than the Grenville. Among the criteria for recognizing their igneous origin are: preservation of original rock textures, such as the porphyritic and the diabasic; relative homogeneity in large bodies; common occurrence of distinct inclusions of older rocks; intrusive contacts, often with dikes from the large bodies penetrating the older rocks; very common occurrence of zircon and zoisite in fresh, well-crystallized grains.

THE GRENVILLE AND ITS FOLIATION

FOLDING OF THE GRENVILLE

Character of the Grenville series.—The Grenville series comprises the oldest rocks of the Adirondack region, and they are, in fact, among the most ancient known rocks of the earth's crust. They consist of a great mass of thoroughly crystallized sediments, such as limestones, sandstones, and shales which have been changed to crystalline limestones, quartzites, and various gneisses and schists. A more or less well-developed foliation is always parallel to the stratification surfaces which are usually distinctly preserved in spite of the crystallization. Granulation is not common. Grenville strata are well represented throughout the Adirondack region, their distribution being very irregular or "patchy" in small to large areas. They are considerably less extensive than the later (intrusive) syenite-granite series, which latter, together with the Grenville, makes up the great bulk of Adirondack rocks. Neither top nor bottom of the Grenville series is known, though thicknesses of from 10,000 to 20,000 feet are actually shown in single sections, and the total thickness is doubtless much greater. Adams and Barlow report a Grenville section about eighteen miles thick in Ontario. The strata are often tilted at high angles or very moderately folded, and sometimes locally contorted. There is a general tendency toward a northeast-southwest strike of Grenville masses in the Adirondacks, but there are many important exceptions.

Grenville series generally regarded as highly folded and compressed.—It has been quite generally assumed by all (including the writer) who have carried on geological work in the Adirondack region that the Grenville strata have been severely compressed and folded as well as thoroughly metamorphosed and foliated by the compression. A few citations from the more recent publications will illustrate the ideas usually held. "There is abundant proof that the rocks have undergone great compression and have been folded and faulted on an extensive scale."[1] The Grenville rocks "have been greatly compressed and intricately folded and plicated."[2] "The old sedimentary rocks have undergone complete recrystallization, entirely obliterating their old textures, and, as a result of severe compression, have had a development of cleavable minerals along certain parallel planes, the mineral particles having a common orientation."[3] "In pre-Potsdam time the pre-Cambric sediments had been tremendously folded and faulted and intruded at great depths."[4] "After the intrusions the whole region was subjected to intense compression and metamorphism when the gneissic or foliated structure of all the rocks was developed."[5]

An alternative hypothesis.—That the Adirondack Grenville strata are more or less folded is admitted at the outset, but, in the light of recent studies, the writer doubts the interpretation of the folded, tilted, and foliated structures as due to intense lateral compression. Certain evident features of the Grenville strata and related intrusives are directly opposed to this interpretation, while all of the structural features may be much more satisfactorily explained in another way. Thus it is conceived that the originally horizontal, or at most only very moderately folded, Grenville strata were much broken up and tilted in masses great and small, and in other cases actually domed, by the irregular upwelling of the great bodies of magma (especially syenite-granite) under only very moderate lateral pressure. This alternative explanation will be developed at some length in its application to the Adirondack region.

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[1] D. H. Newland, *New York State Mus. Bull.*, No. 111, 1908, p. 20.

[2] H. P. Cushing, *ibid.*, No. 145, 1910, p. 9.

[3] *Ibid.*, No. 95, 1905, p. 400.

[4] I. H. Ogilvie, *ibid.*, No. 96, 1905, p. 478.

[5] W. J. Miller, *ibid.*, No. 170, 1914, p. 77.

Evidence against intense folding of the Grenville.—In spite of the assumption of severe lateral compression, no large-scale example of intense folding of the Grenville has ever been positively demonstrated in the Adirondacks, and this in the face of the fact that many hundreds of square miles have been mapped in detail. Describing the Grenville structures of the Elizabethtown–Port Henry quadrangles, Kemp says: "The dips are prevailingly moderate and the ancient sediments appear to have been folded or tilted to only a moderate degree."[1] Regarding the Long Lake quadrangle, Cushing says: "Nearly east and west strikes prevail, and the prevalent dip is southward. This either indicates comparatively little folding, or else isoclinal folding, or else that the foliation does not coincide with the bedding and so does not bring out the folding. It is not possible to demonstrate which of these alternatives is the true one, though the second is very unlikely, and all the direct evidence obtainable is against the third."[2] He also states that in the largest Grenville belt "the dips are so flat that they can seldom be made out with certainty."

The writer[3] has described a structure section in the Broadalbin quadrangle four miles long across the strike of Grenville strata with dips of 20–30° to the southeast. The exposed thickness of Grenville is about 10,000 feet with no repetition of beds due to possible isoclinal folding and no field evidence for profound faulting. Another Grenville section recently described by the writer[4] in the North Creek quadrangle is five miles long with a pretty uniform dip of from 40° to 50°, thus showing a thickness of some 18,000–20,000 feet of strata. There is no evidence of repetition of strata by either folding or faulting. The Grenville is extensively developed throughout this quadrangle, and all the available evidence points to only moderate deformation of the strata either by tilting or slight folding.

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[1] J. F. Kemp, *New York State Mus. Bull.*, No. 138, 1910, p. 85.

[2] H. P. Cushing, *ibid.*, No. 115, 1907, p. 485.

[3] W. J. Miller, *ibid.*, No. 153, 1911, p. 13.

[4] *Ibid.*, No. 170, 1914, p. 15.

According to Cushing, "the foliation strike over much of the Saratoga quadrangle is nearly east-west, and the dips are to the south and rather flat, seldom reaching 45°. As elsewhere, a great monocline of the rocks is suggested, and, as elsewhere, this makes a Grenville succession of enormous thickness, so thick as to suggest caution in the interpretation of the structure, and as to emphasize the probability of the alternative suggestion that the rocks are closely pinched and folded in a series of closed, overturned folds."[1] It is, however, by no means necessary to assume that such common occurrences of monoclinal dips may be due to isoclinal folding. The breaking up and tilting of many blocks or belts of Grenville strata into general parallelism with the upwelling bodies of magma could quite conceivably have taken place under only very moderate lateral compression at most, and, in such cases, monoclinal dips are just what would be expected. This matter will be more fully discussed below.

In the Little Falls, Remsen, Port Leyden, and Lake Pleasant quadrangles, which are also mapped in detail, the Grenville is only sparingly represented, but none of the field evidence points to profound folding of the strata due to lateral compression.

The recent (1913–14) survey of the Blue Mountain quadrangle by the writer has thrown important light on the structure of the Grenville series which is there extensively represented. The great Panther-Snowy mountain mass (altitude 3,900 feet) of syenite occupying the southern portion of the Blue Mountain and the northern portion of the Indian Lake quadrangles is completely bounded on the west, north, and northeast by an unbroken belt of Grenville (mostly limestone) whose strikes and dips show it to lap up on the flanks of the mountain mass of igneous rock for many miles. The curving strike of the igneous rock is also essentially parallel to that of the Grenville. It is evident that we have here a large-scale example of the raising or doming of Grenville over the surface of the great body of uprising magma, the general cover having been removed by erosion, leaving only the circumferential belt of Grenville strata. The higher portions of the syenite now rise fully 2,000 feet above the Grenville. This large-scale tilting of Grenville strata is certainly not due to severe lateral compression, nor is there, in any part of the quadrangle, evidence of highly folded or compressed Grenville strata.

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[1] H. P. Cushing, *ibid.*, No. 169, 1914, p. 30.

In the northwestern part of the Thirteenth Lake quadrangle the writer has examined Chimney Mountain, which is a mass of granitic syenite rising fully 900 feet above a valley on the west. Perfectly bedded Grenville rocks with dip of 50° lap over the whole western face of the mountain of igneous rock, and it seems certain that the tilt of the strata was produced by the rise of the magma.

We are thus led to conclude that none of the published Adirondack geologic maps or available data afford any reason to believe that the Grenville strata were ever profoundly folded or compressed. There is, however, much tilting on large and small scales and some very moderate folding. Such structures may be readily accounted for simply by the irregular intrusion or upwelling of great bodies of more or less plastic magma which broke up, tilted, and lifted or domed the masses of Grenville.

Grenville structure in the Thousand Islands and Ontario regions.—The Thousand Islands district forms the connecting link between the Adirondack and Canadian pre-Cambrian areas, and lies to one side of the region discussed in this paper. Having recently studied the Thousand Islands district, Cushing says: "The Grenville beds are now found for most part in highly inclined condition, dips of less than 45° being relatively rare, while those approaching verticality are common. . . . . It has also been shown that the dip is not everywhere in the same direction, but that, with the general direction of strike to the northeast-southwest, the dip, while prevalently to the northwest, becomes at times southeast. . . . . The highly tilted condition of the rock series, and the changing dips seem certainly indicative of folding."[1] He then describes a prominent belt of Grenville strata which he believes has a synclinal structure. But, accepting the existence of this syncline, does such a structure prove the region to have been subjected to an intense force of compression? Large bodies of granite bound this Grenville belt on either side, and it is quite conceivable that the uplifting effect of the intruding masses, possibly accompanied by some crowding or squeezing of the Grenville between the igneous masses, may have produced this very structure. Cushing also argues that "the general parallelism of the foliation of all the pre-Cambric rocks" affords "evidence of thoroughgoing compression of much later date" than the granitic intrusions. But, as will be shown below, such parallelism of foliation is not necessarily due to severe lateral compression. It should be said, however, that in the Thousand Islands region the granitic and Grenville rocks do seem to be more strikingly arranged in parallel northeast-southwest belts than is usual throughout the Adirondacks. It is possible that considerable orogenic forces did operate across the area from the Thousand Islands region northward into Canada, where also the parallelism is notable. Recent study of the Canton quadrangle seems to indicate considerable folding there. Adams and Barlow, in their description of the Haliburton and Bancroft areas, state that the batholiths "are elongated or arranged in lines having a prevailing direction of about N. 30° E., to which direction the strike of the rocks (Grenville) lying between the batholiths in general conforms. This direction constitutes, so to speak, the general strike of the country, and shows that its present structure has been determined, not only by the rise of granite magma, but by the presence of a second factor in the form of a tangential pressure, acting simultaneously."[1] But it is not at all certain that this tangential pressure was really orogenic in character. Even a very moderate compressive force, not at all sufficient thoroughly to fold and plicate the rocks, acting upon the rising magmas would readily account for all the structural phenomena now visible.

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[1] H. P. Cushing, *New York State Mus. Bull.*, No. 145, 1910, p. 109.

Variation of foliation strikes.—Even if we grant a very considerable lateral compression in the Thousand Islands–Canadian region, the Adirondack area, fully a hundred miles across and to the southeast, does not necessarily come under the same category. In fact, while parallelism of syenite-granite and Grenville rock belts and foliation are common in the Adirondacks, there are so many important variations from a northeast-southwest strike that any generalization regarding such a strike of the rock belts is of little significance. A glance at the accompanying sketch map (Fig. 1) will emphasize the fact that various large areas show strikes distinctly out of harmony with a northeast-southwest structure. The unpublished Lake Placid geologic map shows exceedingly variable strikes. Many variations also occur within most of the other quadrangles, more especially the North Creek, Long Lake, and Blue Mountain (unpublished). Within the Lake Pleasant quadrangle, the foliation strikes relatively uniformly northwest-southeast or just at right angles to the assumed force of compression of the region. Papers by Professor Kemp and assistants in the thirteenth, fifteenth, seventeenth, eighteenth, and nineteenth annual reports of the New York state geologist contain many very variable strike observations in the eastern Adirondacks aside from the quadrangles of the accompanying sketch map. It thus seems clear that the Adirondack rocks show strikes which could not possibly have been produced by a severe lateral pressure exerted across

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[1] Adams and Barlow, *Geol. Surv. Can., Mem. 6*, 1910, p. 16.

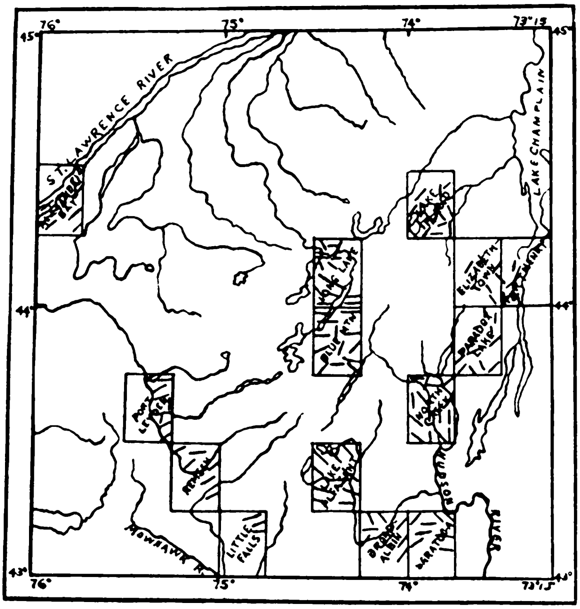

FIG. 1.—Sketch map of the Adirondack region showing generalized strikes of foliation within those quadrangles which have been mapped in detail.

the whole region, for any such pressure, great enough to produce close folding, would have produced a high degree of parallelism of strikes throughout the region.

Local contortions.—Local contortions or sharp folds in the Grenville strata are by no means uncommon, being especially prominent in the limestones and closely associated hornblende and pyroxene gneisses. Such plications have usually been regarded as strong evidence for large-scale folding, being thought of as minor folds superimposed upon large-scale folds. Now, in the first place, it is the writer's experience that such local contortions or plications are very largely confined to the limestone beds, which are easily the most plastic of all Adirondack rocks. In the second place, the crowding of a batholithic magma against the invaded Grenville strata, or the catching of a mass of Grenville between two batholithic magmas, would readily account for more or less local contortions or even puckering of strata without any assumption of orogenic or severe lateral pressure exerted throughout the region. The shouldering action of the upwelling magmas must have produced rather severe local pressures. Regarding the Glamorgan batholith of Ontario, Adams and Barlow say that the Grenville rocks forming the periphery on several sides, "being squeezed between this and the adjacent batholiths, are too highly contorted . . . . to display the prevailing dip distinctly."[1] Evidently such structures do not necessarily call for severe regional compression.

Summary.—To summarize, there is no known evidence within the Adirondack region that the Grenville strata have ever been highly folded or severely compressed, while many broad Grenville belts are known to be only very moderately folded, and many masses, large and small, are merely tilted or domed at various angles. Very locally the strata are sometimes contorted or plicated. The structural relations are therefore best explained as having been the result of slow irregular upwelling of the more or less plastic magmas, probably under very moderate compression, whereby the Grenville strata, previously deformed very little or none at all, were broken up, tilted, and lifted or domed. The stratification surfaces of the Grenville were thus swung into general parallelism with the slow-moving magmatic currents. According to this view, individual large blocks or belts of Grenville strata, or several such blocks or belts separated by intrusive masses, with strike of intrusive masses parallel to Grenville stratification, would be expected to show monoclinal dips; some Grenville masses were shifted around in irregularly rising magmas so as to show various strikes according to directions of movement of the magmas, and hence would not be expected to exhibit monoclinal dips; some Grenville masses were merely domed over bodies of rising magma and would exhibit more or less quaquaversal strikes and dips; while still other Grenville masses were probably bent or even considerably folded into synclines by being caught between bodies of magma upwelling at about the same rate. Isoclinal or close folding on a large scale would scarcely be expected.

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[1] Adams and Barlow, *Geol. Surv. Can., Mem 6*, 1910, p. 15.

In all of this discussion it is important to bear in mind that the Adirondack intrusives occupy a much greater extent than the invaded Grenville rocks, and that, in spite of their intrusive character, they everywhere seem to occupy the position of a fundamental or underlying gneiss. It appears to have been literally true that the Grenville strata were irregularly floated on a vast body of magma, the magma in many places having either arched up or broken through the strata.

ORIGIN OF GRENVILLE FOLIATION

We have just shown that the Grenville strata have never been highly folded or compressed. It is therefore necessary to explain the metamorphism of the strata on some other basis than that of subjection to severe lateral pressure. The old sediments are thoroughly crystallized, and it is certain that they have been reorganized into new minerals under deep-seated conditions; that is to say, they have undergone anamorphic metamorphism. But evidently we are here dealing with a case of essentially static, rather than dynamic, metamorphism.

Origin of parallelism of Grenville foliation and stratification.—The universal parallelism of Grenville foliation and stratification is a fact of prime importance. If the Grenville and accompanying great intrusives had been subjected to compression severe enough to develop the distinct foliation, is it not remarkable that the stratification surfaces have never been obliterated and cleavage developed instead, and also that the stratification and foliation are always parallel? Now, the stratification of the highly crystalline Grenville is remarkably well preserved. Also, unless we assume intense isoclinal folding, so that mineral elongation could everywhere have taken place at right angles to the direction of lateral pressure, the parallelism of stratification and foliation cannot be accounted for by crystallization under severe lateral pressure. We have already shown, not only that there is no positive evidence for such isoclinal folding, but also that there is much positive evidence against any more than the tilting, or, at most, very moderate folding, of the Grenville on large scales.

Again, if the foliation of the Grenville were essentially a dynamic process—that is to say, the result of regional compression after the great igneous intrusions—why should the Grenville be notably less foliated and granulated than the intrusives? (See below.)

We are thus forced to the only alternative conclusion, namely, that the Grenville foliation was developed during the crystallization of essentially horizontal strata under heavy load of overlying material. Those minerals which cause the foliation were elongated during crystallization under heavy downward pressure where conditions of warmth and moisture were also favorable. According to this conception the parallelism of foliation and stratification is precisely what would be expected. It is quite generally assumed that static pressure, that is to say, simple downward pressure, "to the amount exerted in the upper part of the earth's outer crust, appears to have little metamorphic effect."[1] In dealing with the very ancient Grenville, however, it must be remembered that the material now at the surface was once very deeply buried. The thickness of the Grenville series in the Adirondacks is at least some miles and more than likely many miles. Adams and Barlow[2] have recently estimated a thickness of nearly eighteen miles for the Grenville strata in Ontario. It is also definitely known that during pre-Cambrian time the Grenville strata were subjected to tremendous erosion when at least some miles, and quite possibly many miles, in thickness of materials were removed. Thus it seems clear that much of the Grenville rock now visible was once far more deeply buried than any known body of sediments since the beginning of the Paleozoic. Conditions of downward pressure and temperature were, therefore, more than usually favorable for static metamorphism. On the basis of static metamorphism it is not necessary to account for a high degree of metamorphism, because the Grenville series, though thoroughly crystalline, is mostly only moderately foliated with relatively little granulation, and with stratification generally well preserved. It may also be suggested as a possibility that actual crystallization did not begin until an early stage in the intrusion of the slowly upwelling magmas when additional heat for regional metamorphism was supplied.

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[1] L. V. Pirsson, *Rocks and Rock Minerals* (1909), p. 335.

[2] Adams and Barlow, *Geol. Surv. Can., Mem. 6*, 1910, p. 33.

Evidence from other sources.—Experimental evidence is also suggestive in this connection. Thus, Becker and Day[1] have proved that crystals in general have a strong tendency to grow (or elongate) most rapidly at right angles to the direction of pressure. According to Wright,[2] cubes of glass formed by melting together wollastonite, diopside, and anorthite heated to the state of incipient crystallization under vertical pressure, showed, under the microscope, that the three minerals crystallized with long axes at right angles to the direction of pressure. Experimental evidence, therefore, strongly supports the possible development of elongated crystals in the Grenville sediments under conditions of static metamorphism.

Van Hise has suggested, regarding the parallelism of foliation and bedding in the Grenville series, that "vertical shortening and consequently horizontal elongation below the level of no lateral stress may have *begun* the process."[3] The writer views this as essentially the *whole* process, instead of assuming, as Van Hise did, that foliation parallel to bedding continued to develop under certain peculiar conditions when the rocks were subsequently folded. The explanation of foliation parallel to bedding is greatly simplified when it is not necessary to consider severe compression of the region.

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[1] Becker and Day, *Proc. Wash. Acad. Sci.*, VII (1905), 283–88.

[2] F. E. Wright, *Am. Jour. Sci.*, 4th series, XXII (1906), 226.

[3] C. R. Van Hise, *U.S. Geol. Surv., 16th Ann. Rep.*, Part I, p. 773.

Describing the metamorphism of the Shuswap pre-Cambrian series in the Canadian Rockies, Daly says: "It is clear that the Shuswap series has not been seriously affected by dynamic metamorphism. The strata and most of the injected granites were completely or almost completely recrystallized while the strata lay nearly flat. In some localities the effects of dynamic metamorphism have been superposed on those due to previous static metamorphism."[1]

Orientation of Grenville inclusions.—Another fact of importance in connection with the origin of Grenville foliation is the occasional occurrence of well-foliated inclusions of Grenville gneisses variously oriented in the great intrusive bodies. Twenty years ago, in St. Lawrence County, Smyth, noting irregular inclusions of black gneiss in granite, said: "The two foliations, that of the black masses and of the (granite) gneiss, range from parallel with, to perpendicular to, each other."[2] He also noted a similar arrangement of Grenville laminated gneiss inclusions in syenite in Jefferson County. The writer has observed similar phenomena on small and large scales at various localities. Kemp has recently noted inclusions in massive anorthosite and says: "The foliation of the fragments runs in all directions, even in an area of a few square yards. The inference is drawn that the Grenville gneisses were already strongly metamorphosed when the anorthosites entered."[3] It is thus clear, in spite of the usual assumption to the contrary, that the foliation of the Grenville could not have been the result of lateral pressure brought to bear after, or even during, the intrusion of even the oldest of the great igneous masses.

General absence of granulation.—Another fact favoring a process of essentially static metamorphism as opposed to that of dynamic metamorphism is that the Grenville gneisses are, as a rule, comparatively little granulated. Some rather local granulation is to be expected because of magmatic movements, especially where Grenville masses have been crowded against the upwelling magmas. The great intrusive syenite-granite series is very notably more granulated than the Grenville series. How is this fact to be explained if both series have been subjected to strong regional compression after the intrusions?

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[1] R. A. Daly, *Geol. Surv. Can., Transcont. Excur. C 1, Guidebook 8,* 1913, p. 132.

[2] C. H. Smyth, *15th Ann. Rep. New York State Geologist,* 1895, p. 491.

[3] J. F. Kemp, *Geol. Soc. Am. Bull.,* XXV (1914), 47.

THE SYENITE-GRANITE SERIES AND ITS FOLIATION

Character of the syenite-granite series.—The main bulk of syenites and granites in the Adirondacks are regarded by the writer as facies of a single great body intrusive into the Grenville, the intrusives being much more extensively exposed than the Grenville. Perfect gradations from basic (dioritic) facies of syenite to true granite are commonly shown, a quartz syenite being the prevailing rock. As regards granularity, structure, and mineral composition, the members of the syenite-granite series are very variable. The granularity ranges from fine to coarse grain, with medium grain decidedly prevalent. A porphyritic texture is sometimes well developed. Granulation is common, especially in the more acidic rocks, the feldspars generally being notably more crushed than the other minerals. In structure the rocks range from very faintly gneissoid to very clearly gneissoid or sometimes almost schistose, the foliation being accentuated by the roughly parallel arrangement of the dark-colored minerals. The minerals, especially quartz and feldspar, often show more or less flattening or elongation parallel to the foliation. In general the more highly foliated rocks appear to be most granulated. In mineral composition the range is from dioritic types rich in plagioclase, orthoclase, pyroxene, and hornblende; to syenite rich in microperthite, orthoclase, and hornblende or augite together with some quartz and plagioclase; to granite rich in microperthite, quartz, orthoclase, and microcline together with some plagioclase, hornblende, and biotite. Various accessory minerals in smaller amounts also occur. The color of the typical fresh syenite is greenish gray which weathers to light brown, while the fresh granite colors vary from greenish gray to light gray and pinkish gray to almost red. In common with the Grenville, the syenite-granite foliation shows a tendency toward a northeast-southwest strike, with parallelism of syenite-granite and adjacent Grenville quite common, though there are many notable exceptions.

Northeast-southwest structure of rocks.—We have shown that the Grenville series has never been closely folded or severely compressed, and that its foliation was not caused essentially by lateral pressure. The syenite-granite masses, being younger than an intrusive into the Grenville, cannot, therefore, have had their foliation developed chiefly by lateral pressure, though the probable existence of a very moderate lateral pressure is admitted.

In spite of many important exceptions, there is some tendency toward a general parallel northeast-southwest to east-west strike of Adirondack rock masses (Grenville and syenite-granite) and foliation. One view, clearly stated by Cushing, is that "since the rock [granite] solidified it has been subjected to compression, together with the Grenville rocks, giving to each a foliation parallel to the other, and elongating the batholiths in a northeast-southwest direction."[1] At another place he refers to this compression as "thoroughgoing" and of much later date than the granite intrusion. Cushing suggests the possibility of the development of "a similar and parallel foliation"[2] during the solidification of the batholiths due to their shouldering pressure exerted upon the adjacent rocks during the intrusion, but he says that if any such foliation developed it was obliterated by subsequent compression.

The writer's view is that the general northeast-southwest structural parallelism was brought about by just enough tangential compression to control the general directions of the upward-moving batholithic magmas. Accordingly, the intrusive bodies were more or less elongated during the process of intrusion, and there must have been a strong tendency for large and small bodies of previously horizontal, or only slightly deformed, Grenville strata to have been caught up and arranged with their long axes and foliation parallel to the magmatic currents, while the foliation of the intrusives would also have developed, as a sort of flow structure under moderate pressure, parallel to the magmatic currents. This pressure was doubtless in part due to the shouldering effect of the intrusives upon the adjacent rocks. In other words, the syenite-granite gneisses are "primary gneisses." Thus we should expect a general northeast-southwest strike of both rock masses and foliation of Grenville and intrusives to be of common occurrence.

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[1] H. P. Cushing, *New York State Mus. Bull.*, No. 145, 1910, p. 10.

[2] *Ibid.*, No. 145, 1910, p. 102.

A statement made by Smyth twenty years ago regarding black gneiss inclusions in the syenite-granite series of St. Lawrence County is significant in this connection: "The parallel arrangement of the neighboring bands [inclusions] doubtless results from currents in the molten magma, which would tend to produce such a result. It is probable that the breaking into blocks resulted, in part, from strains applied after the magma was in a pasty and partially crystallized state. The blocks were more or less widely separated, and the intervening space was filled by the magma which flowed around the blocks without destroying their angular contour, and, at the same time, often produced an obscure flow structure in the gneiss parallel to the sides of the inclusions."[1] The bandlike inclusions here described by Smyth are seldom more than a few rods long, but the writer believes the principles set forth are applicable on a much larger scale throughout the Adirondack region.

Such parallelism of structural features does not, therefore, demonstrate that the rocks have been thoroughly compressed subsequent to the syenite-granite intrusions. The northeast-southwest structural features here referred to are more pronounced in the Thousand Islands region than is usual throughout the Adirondacks, and this may be readily explained by granting somewhat greater lateral pressure during the intrusion in the first-named region. In any case it is necessary to assume only very moderate compression—far less than would have been necessary to elongate the batholiths and develop distinct foliation in them after their complete solidification.

Exceptions to northeast-southwest structure.—There are many exceptions to the general northeast-southwest structural arrangement, and these prove that no severe tangential compression could ever have been exerted throughout the region after or during the intrusions. Among such exceptions are sharp variations in strike of groups of inclusions of well-foliated Grenville gneiss in the intrusives. Examples have already been cited. If the whole region has been subjected to compression thoroughgoing enough to flatten out batholiths and develop foliation after the consolidation of the magmas, how are these sharp variations in strike of Grenville inclusions to be accounted for? According to the writer's view, such inclusions present no difficulties, because their foliation was produced prior to the intrusions, and some fragments, especially those caught up late in the stiff, nearly consolidated magmas with poorly defined currents, would not have been swung into parallelism in the uprising magmas.

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[1] C. H. Smyth, *15th Ann. Rep. New York State Geologist*, 1895, p. 491.

Also there are important exceptions to parallelism of foliation of adjacent syenite or granite and Grenville gneisses in relatively large areas. A few examples will suffice: eastern side of Port Leyden quadrangle where Grenville with north-south strike is surrounded with syenite with strike N. 30° E.; northwest corner of North Creek quadrangle (see geologic map); near northeast corner of Lake Pleasant quadrangle (see geologic map); northwest of Indian Lake Village; one mile west of Long Lake Village; and in the Broadalbin quadrangle where the large areas of Grenville and adjacent syenite-granite show very different strikes. If the foliation has been produced by compression after the intrusions, how are such sharp differences in strike to be accounted for? Granting the writer's conception that the Grenville was foliated prior to the intrusions, and that the syenite-granite foliation was the result of magmatic flowage, it is to be expected that the magmatic currents would occasionally have broken across the Grenville and its foliation.

Very strong evidence against the development of foliation by compression of the great intrusives is the frequent occurrence of sharp variations in the strike of the foliation, often within short distances. Examination of the Long Lake, North Creek, and Lake Pleasant geologic maps, upon which foliation strikes are plotted, shows many strikes in granite or syenite ranging from parallel to right angles to each other, often within distances of a mile or two. Similar foliation variations occur upon the writer's Blue Mountain and Lake Placid geologic maps, not yet published. How can such foliation variations possibly be explained as due to lateral pressure? If due to compression of the whole region, should not the foliation always strike essentially at right angles to the compressive force?

If, however, we regard the foliation as essentially a sort of flow structure, such phenomena are readily accounted for as due to local variations in the magmatic currents.

Curving strike of foliation.—Still another piece of evidence, though less commonly shown, is the existence of certain broad, sweeping curves in the foliation of syenite or granite. The North Creek, Lake Pleasant, and Long Lake geologic maps show such features. When larger areas of the Adirondacks are mapped in detail, it is probable that more and better examples will be brought to light.

An excellent case of curving of foliation on a large scale is in the Panther-Snowy mountain mass above described as extending nearly across the southern portion of the Blue Mountain sheet and the northern portion of the Indian Lake sheet. The great mass of syenite shows an almost perfect radiation of foliation dips from its center toward the west, north, and east. The only reasonable explanation of such an arrangement of dips is that the foliation was produced as a flow structure in the uprising magma, the most rapid currents having been toward the center of the mass. In the writer's opinion, such a large-scale curved arrangement of foliation strikes and dips not only cannot possibly be explained as due to lateral pressure, since the foliation would then everywhere be practically at right angles to the pressure, but also conclusively proves that no severe compression ever affected the syenite.

Nearly thirty years ago, in his study of the Rainy Lake region, Lawson described a somewhat similar curved foliated structure in granite gneiss and said regarding its origin: "The simplest explanation that suggests itself to account for the structure is that of an uprising force acting on a plastic mass (pasty magma), such force acting with greatest intensity in the vertical line which would correspond to the axis of the cone or dome."[1]

A similar type of structure appears to be common in the Haliburton-Bancroft area of Ontario as described by Adams and Barlow, who say: "Within the batholiths themselves the strike of the foliation follows sweeping curves, which are usually closed and centered about a certain spot. . . . . From these central areas of flat-lying gneiss the dip . . . . is generally outward in all directions. The batholiths, therefore, are undoubtedly formed by an uprising of the granite magma, and these foci indicate the axis of greatest upward movement, and those along which the granite magma has been supplied most rapidly."[1]

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[1] A. C. Lawson, *Ann. Rep. Geol. Surv. Can.* (N.S.), III (1887–88), 116.

There are not only important variations from the general northeast-southwest arrangement of the region within the quadrangles themselves, but also much broader variations shown by a comparison of the average foliation strikes of all the quadrangles of the Adirondacks which have been mapped in detail. This is graphically presented by the accompanying sketch map. Such marked differences in foliation directions on large scales throughout the Adirondacks is certainly incompatible with any idea of thoroughgoing compression of the region. Thus in the Lake Pleasant, North Creek, Blue Mountain, and Saratoga quadrangles the foliation, either wholly or largely, strikes at high angles across the general northeast-southwest strike of the region, while in the Lake Placid quadrangle the strikes are exceedingly variable. If due to compression, the foliation strikes would be much more nearly northeast-southwest than they actually are.

Flow structure character of foliation.—Another significant feature of the foliation should be mentioned, namely, that, while all the minerals are arranged with long axes roughly parallel to the direction of foliation, the dark-colored minerals which accentuate the structure most often appear as narrow, irregular, wavy streaks which are seldom continuous for more than a few inches or a foot. In the writer's experience this type of foliation is by far the most common in the syenite-granite series, and it is believed to be the result of magmatic flowage. Lawson has noted an exactly similar phenomenon in certain granite gneisses of the Rainy Lake region of Ontario and says: "The lines of streaking are very often not straight but are wavy or contorted, sometimes intricately so, and are evidently due to flow movements in the magma prior to its final consolidation."[2] As already suggested, flow structures are locally very distinctly developed, especially around some of the inclusions in syenite or granite.

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[1] Adams and Barlow, *Geol. Surv. Can., Mem. 6*, 1910, p. 14.

[2] A. C. Lawson, *Geol. Surv. Can., Mem. 40*, 1913, p. 93.

Differences in degree of foliation.—Another important consideration is the frequent pronounced variation in degree of foliation in the rocks of the syenite-granite series. They are mostly distinctly gneissoid, rarely so much so as to be almost schistose, while in other cases they are so faintly gneissoid as to be practically massive. A striking feature is the frequent rapid change within a few rods or yards, from rocks which are very clearly gneissoid to others in which the foliation is scarcely discernible. Sometimes, within a foot or two, a very gneissoid zone lies between others which are only moderately foliated. In many cases there is no evidence whatever of shearing to account for these variations. It seems impossible to conceive that such abrupt foliation changes could ever have been produced by severe compression of the rocks after solidification. Such compression would certainly have brought about a much more uniform degree of foliation.

According to the writer's view, these variations are best explained as due to forced differential flowage in the pasty magmas, probably after partial consolidation. Regarding the origin of igneous rock foliation, Pirsson says: "Sometimes this texture has been imposed upon the igneous rocks after they had solidified, by intense pressure and shearing, and sometimes while they were still soft, pasty, and crystallizing, by forced differential flowage, due to various causes."[1] Those portions of the magma which were forced in probably a more fluid condition between other, probably more pasty or solidified, portions would have had a more perfectly developed foliated structure.

According to Leith: "Many more schists than gneisses have been proved to be the result of mashing of igneous rocks. . . . . In fact, so commonly do the igneous rocks appear when mashed to take on schistose as contrasted with gneissic structure as to raise the question whether gneisses are not exceptional results, most gneisses to be explained as igneous rocks with original flow structures."[2] The evidence from the Adirondacks is in harmony with this statement by Leith, since anything like true schists are very rare if not wholly absent from the syenite-granite series.

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[1] L. V. Pirsson, *Rocks and Rock Minerals* (1908), p. 356.

[2] C. K. Leith, *Structural Geology* (1913), p. 103.

Significance of granulation.—Granulation of the rocks of the syenite-granite series is of common occurrence. Most of the mineral constituents are more or less granulated, though it is quite the rule that the quartz shows the effects of crushing less than the others. In the greatest bulk of the rock the cataclastic texture shows itself by flattened or irregular lens-shaped quartz individuals, and more or less lens-shaped broken feldspars, imbedded in a mass of small broken feldspar grains together with some crushed quartz and leaves of mica. In many cases more or less thoroughly elongated and crushed hornblende or augite also occur.

This granulation has usually been regarded as proof that the rocks have been subjected to severe lateral compression and crushing after their consolidation. Thus Smyth, keeping in mind the frequent lack of crushing of the quartz, has said: "As the quartz could hardly flow while the feldspar fractured, the conclusion is obvious, and seems to be well grounded, that, in the case of the quartz, there has been crystallization after the production of cataclastic structure in the rock."[1] But does this prove the quartz to be largely recrystallized or of secondary origin? Could not movements in the magma during a late stage of consolidation, and before much quartz (the last to form) had crystallized out, have caused granulation of the earlier-formed crystals, while the quartz would have been more or less unaffected? In explaining the origin of foliation in the granite-gneiss of the Thousand Islands region, Cushing says: "The rock has been much crushed and somewhat recrystallized under compressive stress, since it originally congealed."[2] Now, while some granulation and recrystallization may have taken place after the magma consolidation, it is by no means a necessary inference that the granite has been much crushed and principally foliated after it had congealed. Strong evidence against severe compression of the Adirondack region has been presented in this paper, while the best evidence points to the origin of the foliation as essentially a flow structure developed under moderate

[1] C. H. Smyth, *15th Ann. Rep. New York State Geologist*, 1895, pp. 488–89.

[2] H. P. Cushing, *New York State Mus. Bull.*, No. 145, 1910, p. 102.

pressure. This being the case, it is only necessary to consider that there were movements in the slowly cooling and stiffening magma whereby the minerals already crystallized out were more or less broken and drawn out into a sort of fluidal arrangement parallel to the foliation, while the minerals last to form were much less granulated. A significant point in this connection is that, in rocks which are definitely known to have been subjected to severe compression, quartz is quite generally more granulated than feldspar. Both Leith[1] and Loughlin[2] have emphasized this point. Now, in the Adirondack intrusives, as we have shown, the feldspar is very commonly distinctly more granulated than the quartz, and the evidence is, therefore, opposed to deformation of the Adirondack rocks by severe regional compression.

The facts that degree of foliation and granulation often vary markedly within a few feet or yards, and that the most perfectly foliated portions are often also the most highly granulated, are to be expected, because flowage in certain portions of the magma during the late stage of consolidation would produce in those portions not only good primary foliation but also notable crushing of the already formed minerals by the movements in the stiff, pasty magma. It seems impossible to explain satisfactorily such marked differences in degree of both foliation and granulation in the syenite-granite series except as the result of movements in the congealing magma. In few cases, if any, is there evidence for shearing, so that if compression of the region be assumed as the cause of the foliation and granulation, it is impossible to explain why adjacent zones often present such differences in degree of foliation and granulation.

Again, the general lack of notable granulation in the oldest rocks of the region—the Grenville—is not compatible with the idea of production of cataclastic structure in the intrusives by lateral pressure, else why were the still older rocks also not proportionately affected?

Other workers have presented strong evidence for the production of a granulated or protoclastic texture in igneous rocks by some such process as that outlined above. Barlow, describing the granite of central Ontario, says: "The movements . . . . continued as the rock cooled and while it was filled with abundant products of crystallization, the movements being brought to a close only by the complete solidification of the rock. Evidence of protoclastic structure can, therefore, be seen throughout all the areas colored as granite or granite-gneiss on the map."[1]

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[1] C. K. Leith, *U.S. Geol. Surv., Bull. 239*, 1905, pp. 33-34.

[2] G. F. Loughlin, *ibid., Bull. 492*, 1912, p. 128.

Teall says, regarding the granite of the county of Kircudbright: "The quartz and alkali feldspar, which . . . . were the last constituents to solidify, are those which have yielded most to the deforming stresses. They show signs of crushing. . . . . It is probable that the pressure acted before the rock mass had actually cooled."[2]

McMahon, discussing the gneissic granite of the Himalayas, says: "It is no argument against the idea of the development of foliation before final consolidation of the granite to point to evidence of strain and mechanical action in the rock; for the existence of strain and mechanical action during the critical period in the history of the granite is an essential part of the theory itself."[3] He admits that the granite has been subjected to lateral pressure but says that this does not prove the foliation to have been produced by such pressure.

Weinschenk,[4] explaining certain schistose Alpine granites, suggests that, in a somewhat advanced stage of magma consolidation, a crystalline skeleton is formed whose interstices are filled with liquid magma. Movements cause crushing of the skeleton, breaking the feldspars and bending the mica plates. Quartz, the last mineral to crystallize, is flattened out but not much broken.

According to Trueman: "It seems not illogical to assume that the movements which were, apparently, present late in the period of consolidation should have sometimes been continued after portions or the whole of the rock had completely solidified. If such were the case there would result considerable recrystallization and granulation so that typical crystalloblastic or cataclastic textures might be superimposed upon that resulting from primary consolidation."[1]

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[1] A. E. Barlow, *Geol. Surv. Can., Mem. 57*, 1915, p. 48.

[2] J. J. H. Teall, *Mem. Geol. Surv. Great Britain, Expl. Sheet 5*, 1896, p. 43.

[3] C. A. McMahon, *Geol. Mag.*, N.S., Decade 4, IV (1897), 347.

[4] E. Weinschenk, *Congrès géol. inter., Compte rendu*, Session VIII, 1 (1900), 341.

The possibility of some granulation and recrystallization in the Adirondack intrusives after complete consolidation is admitted by the writer, but, in view of the evidence above presented, such processes must have had relatively little to do with the development of the textural and structural features of the rocks.

Cause of mineral elongation.—Still another matter to consider briefly is the cause of the flattening or elongation of minerals in the primary gneiss. Flattening or elongation of minerals, especially quartz and feldspar, are common in the Adirondack intrusives, varying from rocks in which the phenomenon is scarcely noticeable to others in which it is extremely developed. It is the writer's experience that many such variations exist within short distances. Quartz exhibits such flattening better and more frequently than the feldspars. The writer believes that the mineral flattening or elongation was caused essentially by crystallization in the magma under pressure. Trueman[2] has recently presented considerable evidence to show that elongation (and presumably flattening) of mineral constituents by crystallization under differential pressure must often have been a very important factor in the production of foliation of primary gneisses.

In the Adirondack syenite-granite series, quartz shows the effects of flattening most because it was the last mineral to crystallize out and hence was not subject to so many of the movements in the magmas. Loughlin presents a similar argument regarding the Sterling granite-gneiss of Connecticut as follows: "After crystallization had become so far advanced that the rock became a mass of feldspar crystals (plus a small amount of quartz) with interstices filled with still fluid quartz, the feldspars would suffer strain, rotation, and slicing, and become a more or less granular lens-shaped aggregate elongated in the direction of least pressure. . . . . As the interstitial quartz began to crystallize, it would be obliged to take on the form of the elongated or flattened interstices."[1]

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[1] J. D. Trueman, *Jour. Geol.*, XX (1912), 244.

[2] *Ibid.*, XX (1912), 235–42.

It is not at all necessary to assume a very active lateral compression of the region to account for this pressure. As suggested by Cushing,[2] considerable compression of the magmas must have resulted from the batholithic intrusions, which, in order to make room for themselves, exerted a shouldering pressure upon the adjacent rocks. It is believed that such a shouldering pressure within the magmas was sufficient, not only to cause more or less flattening and elongation of minerals during consolidation and crystallization, but also to determine to a considerable extent the directions of the magmatic currents and hence the resulting strike of the foliation. Under the very conditions of intrusion, differential pressures must have been common, thus best explaining the frequent variations in degree of flattening of mineral constituents. This view does not of course preclude the possibility of moderate lateral pressure exerted throughout the whole region during, or even after, the magma consolidation.

Foliation of batholithic borders.—Before leaving this discussion another feature of the foliation of the intrusive masses should be mentioned, namely, that they often exhibit a greater degree of foliation and granulation around their borders than in their interiors. This phenomenon seems to be best shown in the anorthosite and the gabbro, and will be discussed below. Suffice it to say here that production of foliation and granulation in the congealing magmas affords a more plausible explanation for the peripheral distribution of such features than their production by compression of the whole region.

Summary.—During the process of intrusion, which was long continued, the great syenite-granite magmatic masses were under only enough lateral pressure to control the general strike of the uprising magmas with consequent tendency toward parallel arrangement of syenite-granite and invaded Grenville masses; the foliation is essentially a flow structure produced under moderate pressure during the intrusion; the sharp variations of strike on large and small scales, and rapid variations in degree of foliation, are essentially the result of varying magmatic currents under differential pressure, principally during a late stage of magma consolidation; the almost universal, but varied, granulation of these rocks was produced mostly by movements in the partially solidified magma, and possibly in part by moderate pressure applied after complete consolidation; and the mineral flattening or elongation was caused by crystallization under differential pressure in the cooling magma.

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[1] G. F. Loughlin, *U.S. Geol. Surv., Bull. 492*, 1912, p. 129.

[2] H. P. Cushing, *New York State Mus. Bull.*, No. 145, 1910, p. 101.

FOLIATION OF THE ANORTHOSITE

It is not the present purpose to discuss thoroughly the origin of the structural and textural features of the Adirondack anorthosite. Only a few of the more important phenomena will be briefly considered. In general, the explanations above given regarding the foliation and granulation of the syenite-granite series apply also to the anorthosite.

Character of the anorthosite.—With the exception of a few small outlying masses, the anorthosite occupies a practically unbroken area of 1,200 square miles in the central-eastern Adirondack region. It quite certainly represents a single great intrusive body which is older than the syenite-granite series. In its typical development the rock consists almost wholly of basic bluish-gray plagioclase and is very coarse-grained, the feldspars often measuring from one to several inches in length. There are several important differentiation variations of the great mass. One of these is coarse-grained, but carries a considerable percentage of dark minerals; another is finer-grained and more gabbroic looking, owing to dark minerals, chiefly augite and ilmenite; while still another facies consists almost wholly of white basic plagioclase, or such white feldspar and more or less dark minerals. The great bulk of the rock is highly feldspathic and practically devoid of foliated structure, probably partly because of lack of minerals favorable for its production or accentuation, while the more gabbroic (especially finer-grained) types are almost invariably well foliated, frequently excessively so.

All of the varieties show more or less granulation, sometimes to a high degree, this being particularly true of the less coarse-grained gabbroic types. As regards amount of granulation of feldspar, it is probably not very different in anorthosite and syenite-granite. The gabbroic, well-foliated, and granulated facies are developed on a grand scale around the borders of the great anorthosite area, but similar types are often encountered irregularly distributed throughout the area. Large feldspar individuals, usually unaltered rounded or lens-like cores of crystals, quite typically stand out prominently in a finer-grained, generally well-granulated, groundmass. In spite of much granulation, it seems certain that the typical original rock (before thorough consolidation) was characterized by a coarse porphyritic texture.

Cause of the foliation and granulation.—The foliation and granulation of the anorthosite has been explained as due to the same severe compression of the region which is supposed to have caused similar phenomena in the syenite-granite series. According to this view, the more general lack of anorthosite foliation is considered to be due to lesser effect of the regional pressure toward the interior of the great intrusive body than around its borders. Also it is thought that coarseness of original grain and general lack of minerals, especially dark minerals, other than feldspar have militated against such complete granulation and foliation of the rock as characterizes the syenite-granite series.

Regarding severe compression after the magma consolidation as the prime cause of the foliation and granulation is, however, open to many of the same objections already discussed in connection with the syenite-granite series. It is the writer's belief that an insurmountable objection to the severe-compression idea lies in the fact that there are so many sudden variations in degree of foliation and granulation, and in strike of foliation, throughout the great anorthosite area. Thus, well within the area, the writer has repeatedly seen very gneissoid gabbroic facies—both coarse and medium-grained—in close proximity to gabbroic facies of similar grain with little or no foliation. All types of anorthosite also often exhibit varying degrees of granulation in close proximity. If they were caused by regional compression, why are so many portions highly foliated or granulated when others close by are unaffected? Also, if regional compression were the cause of the foliation, how are the frequent very notable variations in strike, often within relatively small areas, to be accounted for?

According to the general principles outlined in connection with the foregoing discussion of the syenite-granite series, it is the writer's conception that the foliation and granulation of the anorthosite were developed essentially by flowage or other movements in the magma under moderate pressure, mostly just prior to its complete consolidation. As Cushing has said regarding the Long Lake quadrangle anorthosite: "In some portions of the rock the feldspar crystals are more numerous, are smaller and are all arranged with their long axes parallel. This is a 'flow structure' due to movements in the mass during solidification."[1] The better foliated or better granulated belts throughout the great mass represent merely places where the magmatic currents or other movements were more pronounced. The coarser-grained portions would of course have undergone less complete granulation, but coarseness of grain and absence of dark minerals would not necessarily have tended to prevent the development of foliation. Thus, in the Broadalbin, North Creek, and Lake Pleasant quadrangles the writer has observed coarse granite-porphyry, almost free from dark minerals, with highly gneissoid structure due to thorough flattening out of both quartz and feldspar, while in other cases the porphyry shows little or no foliation. It would seem, therefore, that the general absence of foliation throughout so much of the anorthosite is best explained as the result of the much more uniform intrusion of this single great body which is less involved with Grenville masses, or, in other words, to much less forced differential flowage. Because of its great size, the pressure due to shouldering effect on adjacent rocks would be relatively slighter toward the interior of the mass.

Not only is the foliation well developed around the margin of the great intrusive, but it also appears to be especially well exhibited in many parts of the area in the gabbroic facies where they are close to masses or inclusions of Grenville. Just as flow structure is often best shown close to the wall-rock of, or an inclusion in, a small intrusive body, probably because of friction against the wall-rock or inclusion and consequent development of differential pressure and flowage, so, on a large scale, in the anorthosite body it is reasonable to think that foliation due to magmatic flowage would have been best developed around the margin of, or close to, masses of country rock within the great anorthosite body. In many other places, however, primary gneissoid structures may have been produced by differential flowage far from any country rock.

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[1] H. P. Cushing, *New York State Mus. Bull.*, No. 115, 1907, p. 472.

The cataclastic texture of the anorthosite is believed to have resulted from the crushing of minerals already crystallized out of the stiff, solidifying magma by movements in the magma. The shouldering pressure exerted by the great intrusive mass in order to make room for itself must have been sufficient to have affected the whole mass until final consolidation.

Kemp says, regarding the anorthosite of the Elizabethtown quadrangle: "The entire area has been subjected to such severe pressure and granulation that the outer borders of the crystals are always crushed to a finely granular and whitish mass. Within this rim the bluish nuclei of the plagioclases remain. When shearing and dragging have been added the nuclei yield augen-gneisses."[1] It is, however, not at all necessary to assume severe regional pressure to account for these phenomena. Forced differential flowage in the stiff, nearly congealed magma (under pressure due chiefly to its own shouldering action) could have produced most, if not all, of the granulation and dragging effects, the "augen" being cores of what were large, probably porphyritic, feldspars in the nearly solidified magma. Moderate pressure during or even after consolidation may possibly have operated to accentuate the phenomena.

Adams says, concerning the Morin anorthosite north of Montreal: "The circumstance that the streaks or irregular bands (foliation), when present in the otherwise massive rock, assume no definite direction, but twist about as if owing to movements of the rock while in a pasty condition, indicate that they have been produced by movements before the rock solidified. . . . . The granulation of the coarsely crystalline massive anorthosite, usually with concomitant development of more or less foliated or schistose structure in the way described, is undoubtedly due to movements in the rock, resulting from pressure which acted subsequent to or possibly during the last stages of its consolidation."[1]

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[1] J. F. Kemp, *New York State Mus. Bull.*, No. 138, 1910, p. 28.

FOLIATION OF THE GABBRO

The gabbro here considered is the latest Adirondack intrusive which exhibits foliation and granulation. Diabase is the only intrusive still younger. A few years ago the writer[2] discussed the origin of certain primary variations of Adirondack gabbro. At that time, in accordance with the usual idea, the foliation was thought to be largely a secondary structure and so was omitted from the discussion.

Character of the gabbro.—Most of the gabbro is in the form of small stocks or bosses, the outcropping areas typically ranging from elliptical to almost circular, and the dimensions from a few rods to one or two miles. They are especially well-shown on the North Creek, Long Lake, Elizabethtown, and forthcoming Blue Mountain geologic maps. Most of them are of pluglike or pipelike form, with practically vertical, sharp contacts against the country rock. The stocks exhibit many variations in composition and texture from the normal, homogeneous, dark, basic gabbro with diabasic texture, to lighter-colored rocks of dioritic and even syenitic make-up. They also range from fine-grained to very coarse-grained with feldspars up to an inch or more in length. The typical gabbro contains principally basic plagioclase, pyroxene, hornblende, biotite, garnet, and ilmenite, while orthoclase and quartz often occur in the more acidic facies.

A very important feature, from the standpoint of our present discussion, is the almost universal development of highly foliated amphibolitic borders which often completely surround the stocks, while the interior portions of the typical stocks are usually nonfoliated. In many cases, however, stocks seem to be wholly changed to amphibolite, or only very small cores remain. In still other cases coarse-grained gabbro shows gneissoid structure thoroughly developed throughout. As a rule the gabbro exhibits as good, if not better, foliation than the older intrusives. Often the degree of foliation varies much even well within single stocks.

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[1] F. D. Adams, *Geol. Surv. Can., Guide Book No. 3*, 1913, p. 17.

[2] W. J. Miller, *Jour. Geol.*, XXI (1913), 160–80.

Another very persistent feature is granulation which appears to be of two types, that of so-called "corrosion rims" around certain minerals, and a more generally distributed granulation. Granulated "corrosion rims" occur even in non-foliated gabbro with diabasic texture.

Cause of foliation and granulation.—The foliation and granulation of the gabbro, like that of the older intrusives, are quite generally regarded as secondary features brought about by the influence of regional pressure, the non-foliated, uncrushed cores of stocks being considered as portions protected from pressure influence. Granting the existence of regional compression severe enough to give rise to these phenomena, it is evident that the same pressure must have affected the older intrusives in a similar manner, but this we have proved to be not the case. It is very difficult to imagine a process of development of foliation, which boxes the compass around the borders of the gabbro stocks, by regional compression. Such foliation of course often strikes directly across the foliation of the older adjacent rocks, an excellent case in point being at the south end of the large stock just north of Loon Lake of the North Creek sheet. How can such phenomena be explained as due to regional pressure when it is well known that cleavage or foliation produced by this means must everywhere strike at least approximately at right angles to the direction of application of pressure? Also how are such frequent notable variations in foliation and granulation, not only in near-by stocks but also within stocks, to be explained?

According to the thesis of this paper, the foliation and granulation are largely, if not wholly, primary features. There are, admittedly, some puzzling things about the foliation and granulation of the gabbro, but certainly they are to be much more reasonably interpreted as caused by movements in the magma before complete consolidation.

Weinschenk, in explaining schistose peripheral zones around certain Alpine granitic cores, has suggested: "The consolidation of the rock commenced with the separation of the dark minerals—

biotite and hornblende. Mica formed first in the liquid mass. At this time the orogenic pressure acted upon the peripheral zone of the magma by orienting this mineral normal to the pressure. In the heart of the viscous mass this faculty of orientation was replaced by an interior tension not directed in any particular way."[1] Orogenic pressure did not exist in the Adirondack region, but if for it we substitute the pressures within the stock magmas themselves, this idea of Weinschenk affords a plausible explanation of the foliated borders. Considerable pressures must have obtained within the stock magmas which were intruded under very deep-seated conditions. Such pressure against the country rock, combined with the usual development of differential flowage in the magmatic borders, as already explained in this paper, would readily account for the peripheral foliated zones which were produced, no doubt, during a late stage of magma consolidation. But the conditions for magmatic pressure and flowage must often have varied a great deal, so that it is to be expected that, in some cases, even coarse-grained gabbro would exhibit primary foliation, while, in other cases, amphibolite would make up the whole mass, or, in still other cases, finer-grained, very gneissoid, and granulated belts or bands would occur in the midst of coarser, less foliated types. It should be noted in this connection that unmistakable flow structures do often occur around inclusions in the gabbro.

Applying these ideas, the puzzling features of various gabbro stocks find a ready interpretation. A good example is the stock near Blackbridge in the Lake Pleasant quadrangle.[2] For most part this is a very basic, gabbroic-looking rock, sometimes pretty massive and very coarse-grained, and at other times not so coarse, but streaked or almost banded, owing to layers of amphibolite. All phases of the rock are much granulated and distinctly gneissoid, the coarser-grained portions being least so. A diabasic texture frequently occurs. Differential flowage and other movements under pressure in the congealing magma best explain these phenomena. The more foliated, finer-grained belts in the midst of the coarser, less foliated rock may be readily interpreted as the result of a forcing of slightly more liquid portions of the congealing magma through more solidified portions.

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[1] E. Weinschenk, *Congrès géol. inter.*, *Compte rendu*, Session VIII, 1 (1900), 340. Freely translated from the French.

[2] W. J. Miller, *New York State Mus. Bull.*, No. 182, 1916, p. 29–30.

Highly developed "corrosion rims" are beautifully and extensively developed in the Adirondack gabbros.[1] Their occurrence even in non-foliated gabbro with diabasic texture argues strongly for their production before final consolidation of the magma, this possibility having been recognized by other investigators. How could regional compression have caused so much of this sort of granulation without otherwise affecting the rock? Also, if granulation of this sort has resulted from movements prior to solidification of the magma, why could not the more general cataclastic textures of the syenite-granite, anorthosite, and gabbro have been similarly produced? As in the older intrusives, so in the gabbro, the finer-grained more foliated portions are quite generally the most granulated, this doubtless resulting from more pronounced flowage movements in certain portions of the magma late in the process of consolidation.

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[1] W. J. Miller, *Jour. Geol.*, XXI (1913), 168–70.